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Human Engineering Design Guidelines for a Powered, Full Body Exoskeleton

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This report presents human engineering design guidelines for the development of exoskeletons, which can help the Army do its job faster, safer, with fewer people, and at lower cost by augmenting and enhancing the capabilities of individual soldiers. Descriptions of exoskeletons, which have been developed or attempted, are included to provide background information about previous work in this area. Because many of the tasks that soldiers perform require walking and carrying a load of some kind, the guidelines presented in this report are intended for exoskeletons that are capable of bipedal motion, able to augment the user's strength, and able to enhance the user's endurance. Aspects of anatomy, biomechanics, human performance, and physiology relevant to the design of an exoskeleton are presented. These fundamental human characteristics must be considered in the design of a machine that must work so closely with its user. In addition to the human engineering design guidelines, potential problems associated with exoskeletons are discussed. Finally, areas of the unique interface between the user and the exoskeleton that need further research are listed.

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HUMAN ENGINEERING DESIGN GUIDELINES FOR A POWERED, FULL BODY EXOSKELETON

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July 1995

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U.S. ARMY RESEARCH LABORATORY

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HUMAN ENGINEERING DESIGN GUIDELINES FOR A POWERED, FULL BODY EXOSKELETON

INTRODUCTION

U.S. Army soldiers need help. The size of the U.S. Army is decreasing (725,400 active duty soldiers in fiscal year (FY) 1991 (Ludvigsen, 1992) versus 495,000 active duty soldiers budgeted for FY 1996 (Kalinoski, 1995), but the tasks that must be accomplished on the battlefield are not decreasing. Also, weapons to defeat well-protected enemy systems are becoming heavier. For example, the soon-to-be-fielded advanced antitank weapon system-medium (AAWS-M), Javelin, is more than 1-1/2 times as heavy as the Dragon I, medium antitank weapon fielded in 1975. The Javelin weighs 22.3 kg (49 lb), and the Dragon I weighs 14.0 kg (31 lb) (Biass & Richardson, 1994; Hogg, 1985). By taking advantage of technology, the Army can help soldiers do their jobs better, faster, and safer. One technology the Army can employ is exoskeletons.

Exoskeletons, soldier-worn machines that augment and enhance the strength and endurance of an individual, will benefit the Army in many ways. Because the exoskeleton (not the soldier) will do most of the work, the soldiers will not be fatigued after performing physically demanding tasks. The strength and endurance improvements provided by exoskeletons will mean that the same amount of work or more work can be done with fewer soldiers. This will increase safety by exposing fewer people to dangerous situations. It will also reduce costs because fewer soldiers will be required to complete a task. Examples of military applications of exoskeletons include helping soldiers carry their 45.5- to 68.2-kg (100- to 150-lb) backpacks, maintaining aircraft and vehicles, loading ordnance onto aircraft, loading ammunition onto armored vehicles and tanks, loading air defense missiles onto their launchers, moving artillery rounds from supply vehicles to artillery pieces, loading artillery rounds, loading and unloading supplies, obstacle clearance, and providing a structure on which to attach improved ballistic protection for individual soldiers.

This report presents human engineering design guidelines to be used in developing an exoskeleton. It is not a design specification for an exoskeleton, but rather, it contains information that must be considered in the system engineering of an exoskeleton. This report starts with some background information about exoskeletons and mentions several exoskeletons that have been developed. Because the human and the exoskeleton work so closely together, certain human characteristics must be considered in the development of an exoskeleton. These characteristics

are discussed only briefly. Many of the topics have bodies of literature too extensive to cover here. Next, the guidelines are presented to give designers a starting point for the design of a prototype. Because the operator and the exoskeleton must work together more closely than most machines and operators, potential problem areas are also discussed. Finally, areas of the unique interface between the operator and the exoskeleton needing further research are listed.

BACKGROUND

An exoskeletal machine has a supporting structure surrounding the human operator or some part of his or her body; its movement is synchronized with the operator's movement, and it helps the operator perform strenuous or dangerous work. Many different exoskeletons have been developed. They can be categorized in several ways: by power source, by actuators, by size, by strength, by function, and by application. For purposes of discussion, exoskeletons are divided into two categories here. The first type of exoskeleton is one used to control a teleoperated system (see Figure 1). The motions of the exoskeleton worn by the operator are mimicked by a system some distance away from the operator. Using various means of feedback, the operator is able to remotely control the system and perform strenuous or dangerous work. The second type of exoskeleton (see Figure 2) surrounds the operator, and they move together as one unit. In this type of exoskeleton, the structure has the strength to support itself, the operator, and some or all of the load that the operator is lifting or carrying.

Examples of the first type of exoskeleton, "master" controllers for remotely operated "slaves," include the following systems. The Model I manipulator developed at Argonne National Laboratory was an experimental device which demonstrated the feasibility of an electronically controlled, force-reflecting, servo-manipulator with no mechanical connections between the "master" and "slave" (Goertz & Thompson, 1954). The dexterous teleoperation system (DTS), developed by the University of Utah and others, is a "master" and "slave" arm and end effector designed to perform various tasks in hazardous environments (Smith, Backman, & Jacobsen, 1992). The advanced servo manipulator at Oak Ridge National Laboratory and the Model X force-reflecting hand controller at the Jet Propulsion Laboratory are both six-degree-of-freedom "master" controllers (Remis, 1990). In this case, the number of degrees of freedom refers to the number of axes about which the joints can rotate. Another "master" controller is the seven-degree-of-freedom MB Associates (MBA) exoskeleton. A unique feature of this device is that it allows the operator to manipulate objects and move the exoskeleton around objects in a natural way because it has the same rotational degrees of freedom as a human's arm (Remis, 1990). The sensing and force-reflecting exoskeleton (SAFiRE) and exoskeleton arm master

(EAM) developed by EXOS, Inc., are used to control robots at the National Aeronautics and Space Administration (Eberman & An, 1992). In all these systems, the "master" hand (or hand and arm) control the "slave" hand (or hand and arm).

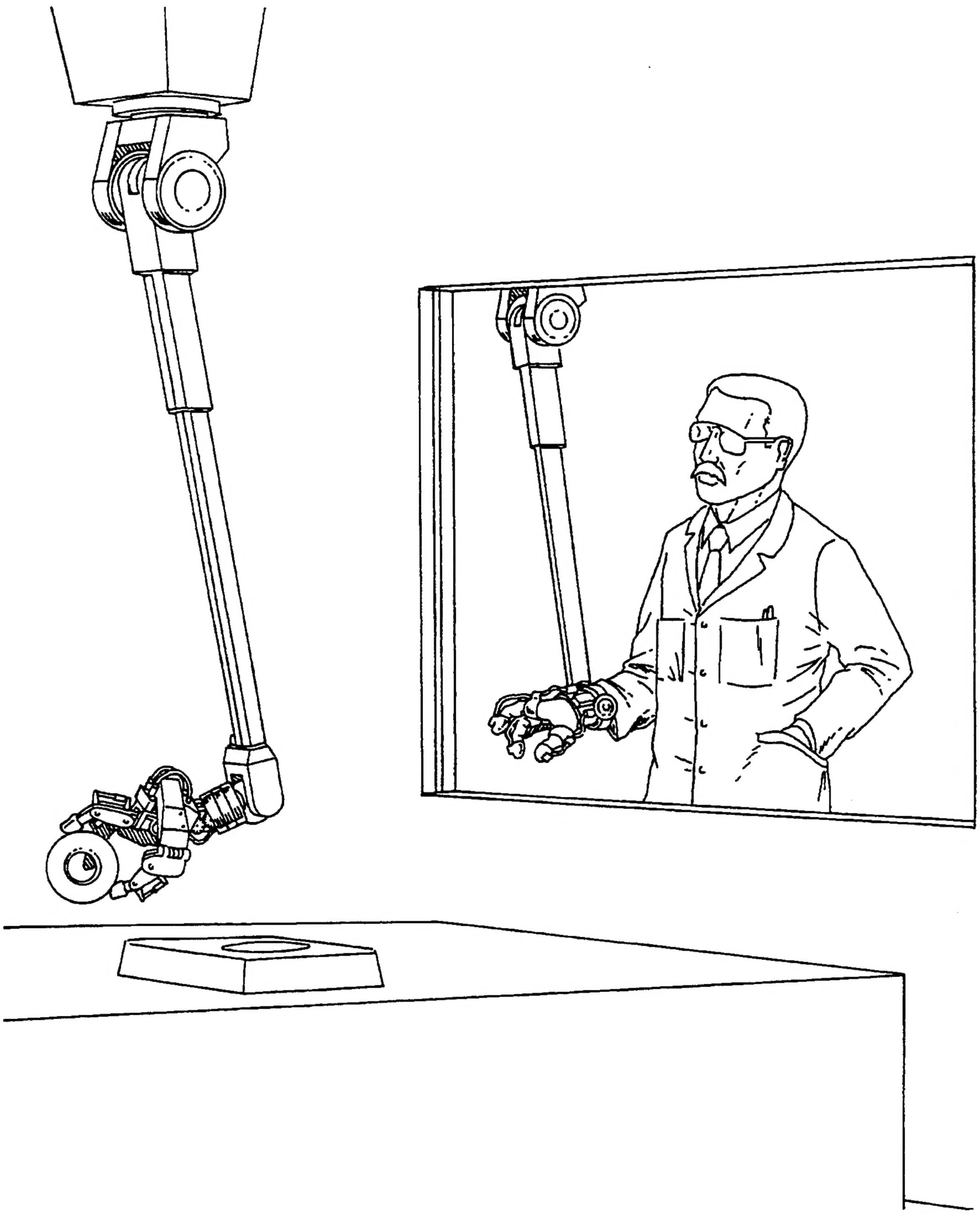

Figure 1. Master controller and remotely operated slave.

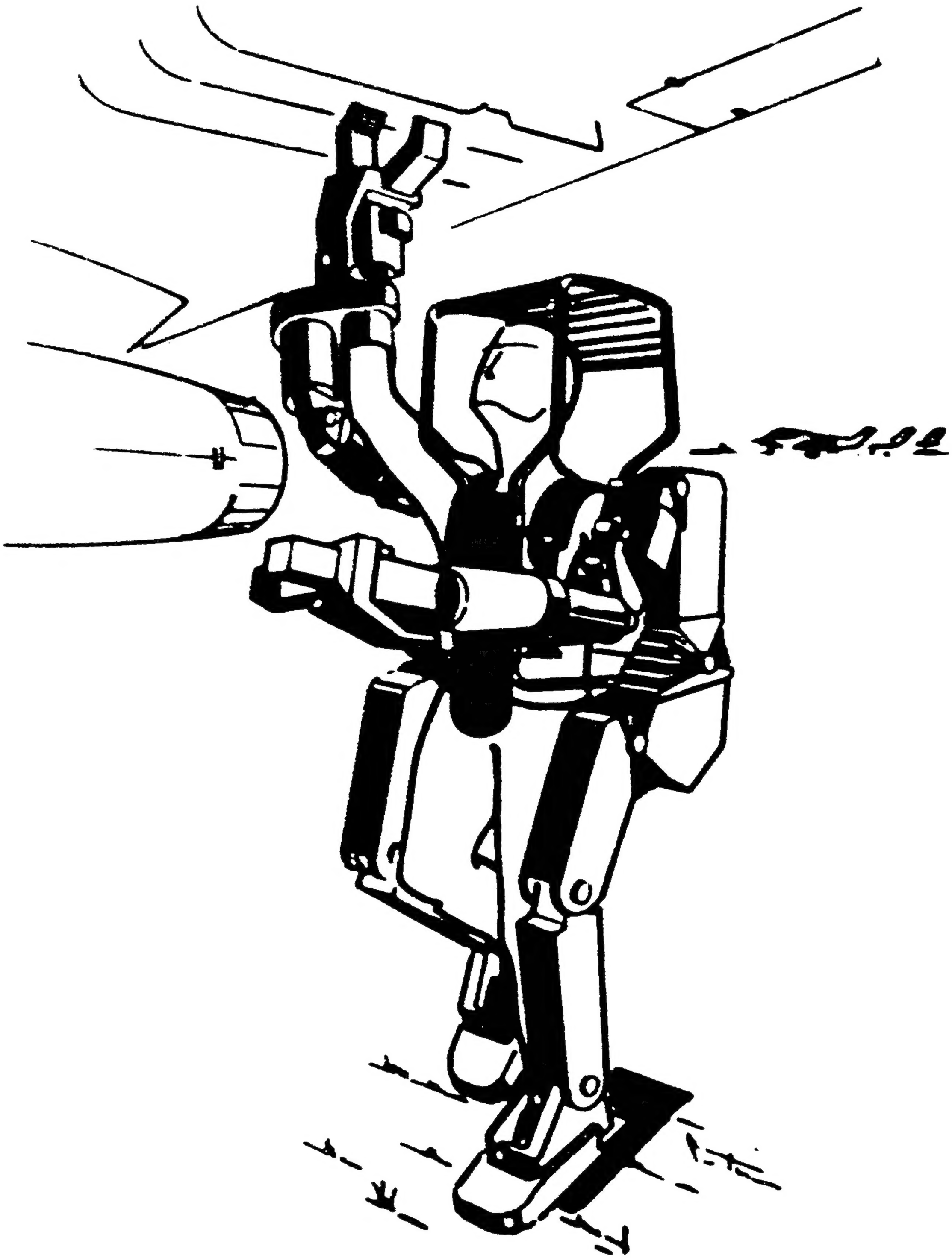

Figure 2. Hardiman I concept drawing (Levin, 1967).

The second type of exoskeleton is designed to enhance the user's strength and endurance for lifting tasks and mobility. Examples of the second type of exoskeleton include the following. Hardiman I, developed by General Electric, was intended to allow the user to lift a load as great as 1,500 lb and carry it 25 ft in 10 seconds. The main problems with Hardiman I were stability of the servomechanisms, safety, and weight and size of the power supply (Levin, 1967). The quadruped walking machine (Mosher, 1973) developed for the U.S. Army Tank-Automotive Command (TACOM) was essentially a vehicle that walked instead of rolling on wheels or tracks. Each leg of the quadruped was controlled by one of the operator's arms or legs. The quadruped demonstrated its ability to carry a 227.5-kg (500-lb) payload over and around obstacles, but because of size and weight limitations, it could not carry its own power supply. An umbilical connected the quadruped to its power supply. A pneumatically powered exoskeleton developed by the Bertin Company (Pavlin & Facon, 1976) and hydraulically powered "extenders" developed at the University of California at Berkeley (Kazerooni & Gou, 1993) are stationary exoskeletons designed to assist with lifting tasks. The pneumatically powered exoskeleton demonstrates the usefulness of fluidic sensors, but it does not provide force amplification. The "extenders" are able to provide force amplification, but they have problems with stability. Vukobratovic, Borovac, Surla, and Stokic (1990) have developed exoskeletons to allow paraplegics and those with weakness of the legs to "walk." Motion is controlled by a computer, and the user's upper body must be supported by crutches or similar means. Additional descriptions of exoskeleton systems and concepts for exoskeletons are in the report by Finkelstein (1993).

Of the two types of exoskeletons mentioned, this document focuses on the second type. The exoskeleton envisioned is capable of bipedal motion, and it will augment the user's strength by allowing him or her to lift and carry heavier objects longer distances. Typical loads might be 45.5 to 91 kg (100 to 200 lb) for a backpack, 32 to 41 kg (70 to 90 lb) for individual artillery rounds, or more than 91 kg (200 lb) shared between two soldiers wearing exoskeletons to load or unload supplies. This exoskeleton will also enhance the user's endurance because it (not the user) will bear most of the weight of the load.

ASPECTS OF ANATOMY, BIOMECHANICS, HUMAN PERFORMANCE, AND PHYSIOLOGY RELEVANT TO THE DESIGN OF AN EXOSKELETON

Human Variability

Human body dimensions differ widely. That is why anthropometric surveys require large samples to characterize a population. Some of the largest anthropometric surveys have been done for the United States military (Gordon et al., 1989; McConville, Tebbetts, Laubach, & Churchill, 1978; White & Churchill, 1977; McConville, Churchill, Churchill, & White, 1977; Clauser et al., 1972; Churchill, McConville, Laubach, & White, 1971). The data collected in these surveys are used mainly to design clothing, protective equipment, and work stations.

The notion that things should be designed to fit the "average man" is false for two reasons (Hertzberg, 1972). First, no one is average for all measurements; in fact, few people are average for more than three or four dimensions. Second, anything designed for the 50th percentile might not work for 50% of the group. For example, a boot designed for the 50th percentile foot length could not be worn by about half of the group because their feet are larger than the 50th percentile.

Because of the variations of human sizes and shapes, it is common practice to design items for the population from the 5th percentile to the 95th percentile. In this way, 90% of the population is covered. As occupations within the military open to women, items are being designed to accommodate sizes from the 5th percentile female to the 95th percentile male (Department of Defense, 1989).

Range of Motion

The joints of the torso, arms, and hands have their own ranges of motion that make possible the complex movements of which humans are capable. The spine can flex and extend, rotate, and flex laterally (Lindh, 1989). The shoulder joint complex, which is comprised of four distinct articulations (glenohumeral, acromioclavicular, sternoclavicular, and scapulothoracic), has a range of motion that exceeds that of any of the other joints. Motions of the shoulder joint complex include flexion, extension, abduction, adduction, rotation, and translation (Zuckerman & Matsen, 1989a). The motions of the elbow include flexion, extension, pronation, and supination (Zuckerman & Matsen, 1989b). The wrist's motions are flexion, extension, abduction, and adduction (Stuchin, 1989). The fingers and the thumb all flex, extend, abduct, and adduct. The thumb also has the capability to rotate (Benjjani & Landsmeer, 1989).

Although walking appears to be a simple activity, which many adults take for granted, many subtle motions occur with each step. Studies of the range of motion of the joints of the human leg during gait show that walking is a three-dimensional activity (Lafortune, Cavanagh, Sommers, & Kalenak, 1992; Õunpuu, 1994). The ankle, knee, and hip joints all experience flexion and extension, internal and external rotation, and abduction and adduction (Isacson, Gransberg, & Knutsson, 1986). Not only do these joints rotate, but the knee (Nordin & Frankel, 1989a) and ankle (Frankel & Nordin, 1989) joints also translate. The foot, which contains many joints, experiences a wide variety of motions including flexion and extension, mediolateral rotation, and translation (Sammarco, 1989).

Joint Centers

An interesting difference between human joints and mechanical joints such as hinges and ball and socket joints is that the joint centers of some human joints move. Although often described as hinges, the ankle (Frankel & Nordin, 1989), elbow (Zuckerman & Matsen, 1989b), and knee (Nordin & Frankel, 1989a) have instantaneous centers of motion, which change as the joints move. Other joints such as the spine (Lindh, 1989) and shoulder (Zuckerman & Matsen, 1989a) also have joint centers that move.

Joint Accelerations and Torques

For the exoskeleton to feel natural for the user, the peak joint velocities, accelerations, and torques must match those of the user. Eberman and An (1992) estimated the peak finger joint velocity to be 26 rad/s and the peak finger joint acceleration to be 150 rad/s^2. Data about the peak velocities, accelerations, and torques of other joints are not available. Remis (1990) also discovered the lack of such data when generating design specifications for a master controller arm that moves like a human arm.

Gait

Human walking is a series of repeated motions. There is a period called the single support phase when the body is supported by one leg while the other leg is swinging forward. There is also a period called the double support phase when the body is supported by both legs. The single support phase lasts about two-thirds of the walking cycle, and the double support phase lasts about one-third of the walking cycle. As walking speed increases and an individual begins to run, the time for double support goes to zero, and there is a period of no support when

both feet are off the ground. The motions of the legs are coordinated with motions of the spine, shoulders, and arms. Spine, shoulder, and arm motions make walking efficient by reducing and braking motions transmitted through the legs and pelvis to the upper body. Energy expenditure in walking is increased if the back is immobilized and rotational motions of the pelvis and shoulders are eliminated. This kind of restriction of the motions associated with walking causes the feeling that maintaining balance is more difficult (Carlsöö, 1972).

Mathematically, human walking can be described by a set of high order, nonlinear, differential equations. These equations cannot be solved unless many simplifying assumptions are made. After all these things occur, the gait that results may be bipedal, but it is not the same as human gait. Robots that walk on two legs have been developed, but their gait is not the same as human gait (Vukobratovic et al., 1990).

Some of the measures used to describe human walking include speed, step length, step frequency, joint range of motion, and muscle activity. There are thousands of studies concerning various aspects of human walking. Some of these studies include Öberg, Karsznia, and Öberg (1993); Waters, Lunsford, Perry, and Byrd (1988); Zatsiorky, Werner, and Kaimin (1994); Murray, Drought, and Kory (1964); Bresler and Frankel (1950); Elftman (1939); and Õunpuu (1994).

Care must be taken when using the results of a gait analysis study. Gait parameters such as speed, step frequency, and stride length are different for indoor and outdoor walking. These same gait parameters are also different for men and women (Öberg et al., 1993). Öberg et al. (1993) found that results apply only to situations that are similar to those in which the data were collected. Öberg et al. (1993) conducted their study on a short walkway in a laboratory. When they compared their data to the data of Waters et al., (1988), collected outdoors on a 60.5-meter (198.5-ft) circular track, they found that gait parameters differ for indoor versus outdoor walking. In general, normal gait speed is slower, step frequency is higher, and step length is shorter for indoor walking on a short walkway compared to outdoor walking. With respect to gender, males generally have a faster gait speed, lower step frequency, and longer step length than females during normal walking.

Balance

When a human stands "still," his or her center of gravity (CG) is over the area of the base of support provided by the feet. Yet, even when standing "still," humans sway. This causes the body's center of pressure (the location of the resultant ground reaction force) to move several millimeters (Winter, Patla, & Frank, 1990).

During walking, the body is in a constant state of imbalance except during the double support phase when both feet are on the ground. At the start of the single support phase, the CG is posterior and medial to the stance heel. As the body moves forward, the CG moves forward, but it does not necessarily pass directly over the base of support provided by the stance foot. Falling is prevented by moving the swing leg ahead of and lateral to the forward moving CG (Winter et al., 1990).

If one's balance should become perturbed during normal walking, for example by tripping, the body's response to recover balance occurs within 100 ms. If the perturbation occurs very quickly or is applied at high levels of the trunk, the response occurs faster, within 46 ms. In response to such a perturbation, the hips, knees, and ankles act to lower the body's CG (Winter et al., 1990).

Performance Degradation When the Operator is Encumbered

Performance of a task when the operator is encumbered by an exoskeleton has been examined by Remis and Repperger (1990). In their experiment, subjects performed peg in hole tasks with and without the MBA exoskeleton. Remis and Repperger used Fitts' Law to make the performance comparison. They found that when the subjects wore the MBA exoskeleton, their information channel capacity (i.e., information processing capacity) decreased 41% for ballistic tasks; it decreased 34% for accurate positioning tasks; and it decreased 32% for one-dimensional tasks. They also found that wearing the exoskeleton increases the subject's physiological reaction time, but this result was reported to be sensitive to the conditions of the experiment.

Remis and Repperger (1990) hypothesize that the information channel capacity is decreased when subjects wear the exoskeleton because the operator is processing information related to such things as joint friction, kinematic constraints, and added inertia. With regard to reaction time, they hypothesize that reaction time increases when subjects wear the exoskeleton

because of the added mass and joint friction. Another explanation they present is that because subjects are wearing the exoskeleton, they need more time to plan their movements.

Noise

Prolonged exposure to loud noises can damage hearing. Standards such as MIL-STD-1474C (Department of Defense, 1991) place limits on exposure to acoustical noise. For example, steady state noise levels of 100 dB(A) are hazardous to unprotected ears and require electrically aided communication to an attenuating helmet or headset. Hearing protection is required for steady state noise levels of 85 dB(A) or more. MIL-STD-1474C applies to the acquisition and product improvement of all designed or purchased ground systems, subsystems, equipment, and facilities that emit acoustic noise. It is intended to cover noise emitted during typical operating conditions and exposures of 8 hours per day. The criteria in MIL-STD-1474C are intended not only to minimize noise-induced hearing loss but also to achieve acceptable speech communication in a noisy environment, minimize aural detection by an enemy, and minimize community annoyance.

Touch Perception and Vibration

Touch perception and vibration are important to the design of a force feedback system. Srinivassen and Eberman (1992) report that the threshold of touch perception is 0.6 gram (0.02 ounce). To enhance cuing, vibration can be used. The maximum sensitivity to vibration occurs at 200 Hz.

Sustained Work Rate

The ability of an individual to work for a long period of time without becoming physically fatigued is important for tasks requiring manual labor. The measure of an individual's maximal aerobic power is his or her VO_2 (max), that is, maximum oxygen intake, and it is usually determined from an exercise test on a treadmill or a bicycle ergometer.

Many studies have examined work rates when the work is sustained for several hours. Based upon bicycle ergometer and treadmill studies, Åstrand (1960) found that men and women could work at approximately 50% VO_2 (max). In another study by Åstrand (1967), men performing construction work worked at an average rate of 40% VO_2 (max). Wells, Balke, and Van Fossan (1957) classify work at 50% VO_2 (max) as "optimal," meaning that it can be

performed for 8 hours per day for a few weeks. This is based on their study of men walking on a treadmill. Michael, Hutton, and Horwath (1961) found that men could walk on a treadmill or ride on a bicycle ergometer at 35% VO_2 (max) for 8 hours without becoming unduly fatigued. Sharp, Knapik, and Schopper (1994) found that during a 45-hour continuous field artillery loading exercise, average exercise intensity started at 49% VO_2 (max) and declined to 37% VO_2 (max) at the end of the exercise. In a study of male soldiers walking hard surface roads while carrying a load, Myles, Eclache, and Beaury (1979) determined the average energy expenditure to be 32% VO_2 (max). In a study of men and women carrying loads over a variety of terrain, Evans, Winsmann, Pandolf, and Goldman (1980) found that self-paced hard work was 45% VO_2 (max) for the test, which lasted 1 to 2 hours. Based upon several studies, the National Institute for Occupational Safety and Health (NIOSH) (1981) recommends a work rate of 33% VO_2 (max) for an 8-hour work day. This applies to men and women working in jobs requiring manual lifting.

Electromyography

One way to characterize muscle activity during such motions as walking or lifting is with electromyography. In electromyography, the electrical activity of a muscle is recorded by means of surface electrodes or needle electrodes inserted into the muscle fibers. When muscles contract, electrical activity can be detected by the electrodes. These voltages range from 10 microvolts to 4 millivolts, and the frequencies range from 25 to 20,000 Hz (Carlsöö, 1972). The electrical activity becomes negligible when the muscles relax. By using a number of electrodes, UCAL Berkeley (1953) made recordings of the electrical activity (or contractions) of various leg muscles during walking. For voluntary isometric contractions of a muscle, the integrated electrical activity measured by surface electrodes is linearly related to the tension exerted (Lippold, 1952). For voluntary contractions at slow constant velocity, the integrated electrical activity is linearly related to the weight raised or lowered by the muscle (Bigland & Lippold, 1954). For voluntary isotonic contractions, the integrated electrical activity is linearly related to the muscle's velocity of lengthening or shortening (Bigland & Lippold, 1954).

If electromyography could output the forces and velocities of individual muscles during dynamic motions, it would be an ideal way to control an exoskeleton. The exoskeleton could then mimic the operator's motions exactly. Unfortunately, electromyography is most useful when the muscle contractions are isometric, isotonic, or slow constant velocity. This means that for many of the dynamic movements associated with lifting, walking, and running electromyography will not give reliable indications of muscle forces or velocities. In dynamic situations, the most useful information that electromyography can give is whether a muscle is activated.

DESIGN GUIDELINES

These are general human engineering design guidelines for the design of an exoskeleton. They are not written as specifications because the intent of this report is not to define a complete system. Also, more research is needed to quantify certain aspects of human performance before specifications can be written.

- The exoskeleton should fit a range of sizes. If the exoskeleton is used only by combat soldiers, the size range can be from the 5th to 95th percentile male. If the exoskeleton is not used exclusively by male soldiers, a broader range of sizes from the 5th percentile female to the 95th percentile male will be needed.

- The joint range of motion should accommodate walking, carrying a load, and getting up from a fall. These are the minimum abilities that a bipedal, full body exoskeleton must have if it is to be useful to the Army. The ideal exoskeleton would have the same degrees of freedom at its joints and the same ranges of motion as a human. This would allow the exoskeleton to mimic all of its user's movements, but the focus of this document is narrower. These design guidelines are intended to be used in the development of an exoskeleton that walks, lifts and carries objects, and gets up from a fall. As a starting point in powered, full body exoskeleton development, the joints of the exoskeleton should have the degrees of freedom (DOF) shown in Table 1. The suggested ranges of motion for the joints of the exoskeleton are given in Table 2.

Table 1

Minimum Degrees of Freedom for Exoskeleton Joints

Joint	DOF	Description
Foot	1	Extension for the metacarpophalangeal joint
Ankle	1	Flexion and extension
Knee	1	Flexion
Hip	3	Flexion and extension, abduction and adduction, medial and lateral rotation
Pelvis	3	Rotations in the coronal, sagittal, and transverse planes
Spine segments	3	Flexion and extension, lateral flexion, rotation
Shoulder	3	Flexion and extension, abduction, medial and lateral rotation
Elbow	2	Flexion, forearm pronation and supination
Wrist	2	Flexion and extension, abduction and adduction

Table 2

Minimum Ranges of Motion for the Exoskeleton's Joints

Joint movement	Range of motion (mean value degrees)	Reference
Metacarpophalangeal extension	90	Sammarco, 1989
Ankle flexion and extension	35 flexion, 38 extension	Barter, Emanuel, and Truett, 1957
Knee flexion	113	Barter, Emanuel, and Truett, 1957
Hip flexion and extension	140 flexion, 15 extension	Nordin and Frankel, 1989b
Hip abduction and adduction	30 abduction, 25 adduction	Nordin and Frankel, 1989b
Hip medial and lateral rotation	70 medial, 90 lateral	Nordin and Frankel, 1989b
Pelvis rotation in coronal plane	8	Õunpuu, 1994
Pelvis rotation in sagittal plane	4	Õunpuu, 1994
Pelvis rotation in transverse plane	8	Õunpuu, 1994
Spine segment flexion and extension	4 (segments T1-T6) 6 (segments T6-T10) 8 (segments T10-T11) 12 (segments T11-L2) 14 (segments L2-L3) 15 (segments L3-L4) 16 (segments L4-L5) 20 (segments L5-S1)	Lindh, 1989

Table 2 (continued)

Spine segment lateral flexion	6 (segments T1-T11) 9 (segments T11-T12) 8 (segments T12-L1) 6 (segments L1-L3) 8 (segments L3-L4) 6 (segments L4-L5) 3 (segments L5-S1)	Lindh, 1989
Spine segment rotation	9 (segments T1-T8) 7 (segments T8-T9) 4 (segments T9-T10) 2 (segments T10-L5) 5 (segments L5-S1)	Lindh, 1989
Shoulder flexion and extension	188 flexion, 61 extension	Barter et al., 1957
Shoulder abduction	130	Repperger, Remis, and Merrill, 1990
Shoulder medial and lateral rotation	97 medial, 34 lateral	Barter et al., 1957
Elbow flexion	142	Barter et al., 1957
Forearm pronation and supination	77 pronation, 113 supination	Barter et al., 1957
Wrist flexion and extension	90 flexion, 99 extension	Barter et al., 1957
Wrist abduction and adduction	27 abduction, 47 adduction	Barter et al., 1957

- For comfort and ease of motion, the joint centers of the exoskeleton should align with the user's joint centers.

- The actuators for the exoskeleton joints must be capable of the joint velocities, accelerations, torques, and duty cycles necessary to move in parity with the user. For the fingers, Eberman and An (1992) have estimated peak joint velocity to be 26 rad/s and peak joint acceleration to be 150 rad/s^2. (Little or no information is available about velocities and accelerations of other joints. Similarly, joint torque and duty cycle data are not available.)

- Wearing the exoskeleton should not require the user to change his or her gait significantly. Otherwise, this will lead to fatigue or will require additional training as the user learns a new gait pattern.

- The controller must be able to keep pace with the user's actions, in particular, actions that must occur quickly such as recovering balance. The sensor-controller-actuator loop must operate in approximately 3 to 5 ms. (This is based on the recommendation of Srinivassen and Eberman [1992] that sensor-controller-actuator processes occur at 5 to 10 times the anticipated bandwidth needed. Actions to recover balance can occur in 46 ms [Winter et al., 1990]. Operations at ten times this bandwidth take 4.6 ms. Also, Remis [1990] defined control loop throughput of 4 ms or less as a performance goal for a new master controller being designed for the Air Force.)

- The limbs of the exoskeleton must be counterbalanced or gravity compensated across the range of loads to be carried so that the user does not feel like he or she is carrying the weight of the exoskeleton.

- The exoskeleton must be able to stay upright and balance itself, but it must also allow for normal sway when the user is standing "still." Normal swaying should not be interpreted as a motion to be amplified because this will waste power, and it could cause the exoskeleton to oscillate out of control.

- The exoskeleton should be designed so that it is easy to learn how to use and maintain.

- The system must not be so noisy that it is hazardous to the user's hearing. To avoid the requirement for hearing protection and electronically aided communication, the steady state noise limit should be less than 85 dB(A) based on a maximum daily exposure of 8 hours (MIL-STD-1474C) (Department of Defense, 1991).

- The exoskeleton must not be so noisy that it is easily detected by the enemy. The detection distance will depend upon how the exoskeleton is used. The acceptable noise of the exoskeleton can be determined from the detection distances in Tables III and IV of MIL-STD-1474C.

- The exoskeleton should not be so noisy that it interferes with speech communication or requires electronically aided communication. Therefore, from MIL-STD-1474C, if occasional

shouted communication as far away as 0.60 m (2 ft) will occur, the noise level must be less than 85 dB(A). If occasional telephone or radio use or occasional communication at distances as far as 1.50 m (5 ft) will occur, the noise level must be no more than 75 dB(A). If frequent telephone or radio use or frequent communication at distances as far as 1.50 m (5 ft) will occur, the noise level must be no more than 65 dB(A). If more than one individual involved in face-to-face communication is wearing an exoskeleton, the additional noise of the other exoskeleton(s) must be considered.

- The exoskeleton must include force feedback.

- The work rate required of the user in the exoskeleton should be one-third to one-half of his or her maximum aerobic power (VO_2 (max)). This will allow the user to work in the exoskeleton for an extended period of time without becoming fatigued. This guideline has a range because consideration must be given to the task, the period of time required to accomplish the task, and the physical condition of the user. If the user is required to perform very strenuous tasks for a 1 to 3 hours each day, he or she should be able to work at a rate as great as 50% VO_2(max). If less physically demanding tasks are done during the entire work day, a user should be able to work at a rate of 33% VO_2 (max).

- Attachments between the exoskeleton and the user must not cause bruising, pressure sores, or abrasions.

- Sensors must be located so that they do not misinterpret muscle movement as gross movement. For example, when the arm flexes to lift an object, the biceps brachii muscle changes shape. This change of shape should not activate a sensor and initiate other movements by the exoskeleton arm.

- The exoskeleton must be easy to don and doff.

- From the standpoint of hygiene and maintainability, the materials from which the exoskeleton-to-user interface is made should be resistant to sweat electrolytes and water.

- For safety reasons, the interface between the exoskeleton and the user should be designed so that slippage is minimized when users sweat or get wet from precipitation.

- Exhausts, fuels, and other fluids used to power the exoskeleton should not be hazardous to the user.

- If the power supply or any other part of the exoskeleton generates a large amount of heat, it should have heat shields or guards around it to keep the user from getting burned.

- For safety reasons, the limits on lifting with the exoskeleton should be defined for the user.

- The exoskeleton should be designed so that it cannot exceed its limits for lifting. If that is not possible, the exoskeleton should warn the user when the limits of safe lifting are being approached.

- If the exoskeleton fails, it must fail in a safe mode so that the user is not injured and can exit safely.

POTENTIAL PROBLEM AREAS

Clothing must also be considered when one is designing something for humans to use. Some clothing is intended to fit tightly; other clothing fits loosely, and clothing adds to the volume occupied by a person. Allowances need to be made for various types of clothing the user might wear. For example, in cold climates, the exoskeleton should not compress the soldier's clothing so much that it loses its insulating qualities. Conversely, in hot climates, an exoskeleton could interfere with the dissipation of heat from the user's body. The problem to be solved is whether the exoskeleton will be worn under the user's clothing, over the user's clothing, or over some clothing and under others. This may in turn affect the sizes or styles of uniforms that are worn with an exoskeleton.

Wearing an exoskeleton will increase the user's volume. This may make it difficult to maneuver in certain work spaces and enter and exit some vehicles.

Wearing an exoskeleton may change the user's gait. This will depend upon how many degrees of freedom the exoskeleton has, the range of motion of the joints, the fit, and the locations of the joint centers. If the user's gait is altered, his or her endurance will be adversely affected. This may require a large amount of training time with the exoskeleton as muscles are strengthened and used in ways they are not normally used. Short initial training sessions with the exoskeleton

will be needed to let the user's muscles adapt to the new gait and to reduce muscle soreness during training.

Using an exoskeleton will degrade the user's information channel capacity and increase his or her reaction time as Remis and Repperger (1990) showed. This has implications for training, command, control, communications, and selection of soldiers capable of using an exoskeleton. Considerable training may be required to familiarize the user with the exoskeleton so that he or she can adjust to the increase in reaction time and the degradation in the information channel capacity. The decrease in the information channel capacity may limit the amount of command, control, and communication information that can be passed to or from the user. Depending upon how much the information channel capacity is degraded and whether the reaction time is increased, it may be appropriate to limit exoskeleton use to certain soldiers. Perhaps, only soldiers who can compensate for the degraded performance by virtue of their innate abilities will be selected to use an exoskeleton.

AREAS NEEDING FURTHER RESEARCH

Although much information is known about the human body and how it works, more information is needed to develop a powered, full body exoskeleton. Unique features of the interface between the operator and the exoskeleton must be understood in greater detail. Because the operator and the exoskeleton must work together so closely, it is essential to design the exoskeleton to be as safe, efficient, natural, and intuitive as possible for the operator. The following areas require further research.

The available anthropometric data are measured using landmarks that usually are not the joint centers. The lengths of the links of the exoskeleton will be the joint center to joint center distances. Therefore, the available anthropometric data need to be adjusted to give joint center to joint center distances, or new data need to be collected.

Because wearing an exoskeleton will add to the user's volume, the tasks within the missions of an exoskeleton that have volume constraints need to be defined. Also, the nature of those constraints needs to be defined.

To increase the use of exoskeletons within the Army, the range of motion required for other militarily significant movements such as running, crawling, and climbing needs to be determined.

Research is needed on the peak joint velocities, accelerations, and torques. Joint duty cycles also need to be investigated. This information is required to specify actuators.

The feedback needed to operate the exoskeleton must be determined.

The question must also be answered about how much performance can be degraded by friction, reduced perception, increased reaction time, reduced information channel capacity, and movement restrictions before the exoskeleton is no longer beneficial to the user.

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